# Mirror World versus large extra dimensions

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**Abstract**

Recently proposed low scale quantum gravity scenario is expected to have a significant impact on the Mirror World hypothesis. Some aspects of this influence is investigated here, assuming that the fundamental gravity scale is near a TeV. It is shown that future colliders will be capable of producing the mirror matter, but an experimental signature, which will distinguish such events from the background, is not clear. The "smoking gun" signals of the Mirror World would be an observation of decays like $\Upsilon(2S) \to \tilde{\chi}_{b2}\gamma$. But unfortunately the expected branching ratios are very small. Finally, it is shown that a mirror supernova will be quite a spectacular event for our world too, because a considerable amount of ordinary energy is expected to be emitted in the first few seconds.

## 1 Introduction

Despite firmly established V-A character of weak interactions, "the violation of parity invariance is, remarkably, still an open question" [1]. It is not yet excluded experimentally that every ordinary particle is accompanied by its mirror twin. This dramatic duplication of the world restores left-right (and time reversal) symmetry of Nature, provided that the mirror particles experience V+A (mirror) weak interactions [1, 2]. The idea itself dates back to the seminal paper of Lee and Yang [3], but it remained rather unfruitful until a phenomenological analysis of Kobzarev, Okun and Pomeranchuk [4] appeared, where the term "Mirror World" was coined for the first time. A number of papers had followed [5], and it became clear that the main, if not only, connection between two worlds should be provided by gravity.

Recently the Mirror World scenario has revived in connection with neutrino physics [1, 2, 6, 7, 8]. Parallel Standard Model [6, 7, 8] – the Standard Model doubled by the mirror sector, appears to be a viable candidate for the Standard Model extension. The new parity symmetry (which also interchanges ordinary and mirror particles) can still be violated spontaneously [6] during electroweak symmetry breaking, leading to a quite different macrophysics for the Mirror World [6]. But esthetically more appealing seems the possibility for the full Lorentz Group to be an unbroken symmetry of Nature. Although such Exact Parity Model [7] assumes that the symmetry breaking patterns are strictly correlated in two (ordinary and mirror) worlds – an ultimate example of the Einstein, Podolsky, and Rosen paradox [9].

Besides data on neutrino oscillations, which may support existence of sterile neutrino(s) (see however [10]), where are some other phenomena which can be also interpreted as indicating towards the Mirror World:

- The mirror matter can constitute a considerable fraction of the dark matter [11].
- The observed gravitational microlensing events can be caused by mirror stars [8, 12].
- The deficit of local luminous matter revealed by the recent Hubble Space Telescope star counts [13, 14] was predicted by Blinnikov and Khlopov (1983) [5] as a result of mirror stars existence.

- The mirror neutrinos and mirror stars can play crucial role in cosmic Gamma-ray Bursts [14, 15].

Gravity is the main connector between our and mirror worlds. But it was recently suggested [16] that the apparent weakness of gravity can be just a low energy phenomenon caused by the existence of new sub-millimeter scale spatial dimensions, in which gravitons propagate freely in contrast to the Standard Model fields which are confined to a three-dimensional wall ("3-brane"). In this case, at high energies of about a TeV, gravity becomes strong, comparable in strength to the other interactions. Upcoming collider [17] and/or gravity [18] experiments will soon uncover whether such low scale quantum gravity scenario has something to do with reality. Meanwhile we can speculate about the impact that the existence of the large extra dimensions will have on communications between our and mirror worlds.

It may happen that the visible matter and the mirror matter are located in two different 3-branes [19]. Such literally parallel world will be connected to the ordinary one necessarily very weakly due to exchange of massive Kaluza-Klein excitations [19]. Remarkably enough, recent alternative proposal of Randall and Sundrum [20] for solving the Hierarchy Problem is based on the model with two parallel 3-branes!

But in this work we will assume that both the ordinary and the mirror particles live in the same 3-brane. In this case low scale quantum gravity implies several new phenomenological consequences for mirror matter searches.

## 2 Mirror matter production at colliders

One immediate new feature of a TeV scale quantum gravity is the possibility for mirror particles to be produced at future high energy colliders. Using Feynman rules given in [21], we can get, for example (mirror particles are denoted by tilde throughout the paper)

$$\frac{d\sigma(e^+e^-\to\tilde{e}^+\tilde{e}^-)}{dt}=\frac{\pi s^2}{32\Lambda^8}\left\{1+10\frac{t}{s}+42\left(\frac{t}{s}\right)^2+64\left(\frac{t}{s}\right)^3+32\left(\frac{t}{s}\right)^4\right\},\tag{1}$$

where $\Lambda\sim 1\mathrm{T}eV$ is an ultraviolet cutoff energy for the effective low-energy theory, presumably of the order of the bulk Planck mass [21]. For the total

cross-section we obtain

$$\sigma(e^+e^- \to \tilde{e}^+\tilde{e}^-) = \frac{\pi s^3}{160\Lambda^8} \approx 7.6 \left(\frac{s}{\mathrm{Te}V^2}\right)^3 \left(\frac{\mathrm{Te}V}{\Lambda}\right)^8 \ \mathrm{p}b. \tag{2}$$

Other examples are

$$\begin{aligned}
\frac{d\sigma(e^+e^- \to \tilde{\gamma}\tilde{\gamma})}{dt} &= \frac{\pi s^2}{8\Lambda^8}\left(-\frac{t}{s}\right)\left(1+\frac{t}{s}\right)\left(1+2\frac{t}{s}+2\frac{t^2}{s^2}\right), \\
\frac{d\sigma(\gamma\gamma \to \tilde{\gamma}\tilde{\gamma})}{dt} &= \frac{\pi s^2}{2\Lambda^8}\left[\left(1+\frac{t}{s}\right)^4+\frac{t^4}{s^4}\right].
\end{aligned} \tag{3}$$

Which translates into the following total cross sections ($\frac{1}{2}$ is included to account for identity of the final state photons)

$$\begin{aligned}
\sigma(e^+e^- \to \tilde{\gamma}\tilde{\gamma}) &= \frac{\pi s^3}{320\Lambda^8} \approx 3.8 \left(\frac{s}{\mathrm{Te}V^2}\right)^3 \left(\frac{\mathrm{Te}V}{\Lambda}\right)^8 \ \mathrm{p}b, \\
\sigma(\gamma\gamma \to \tilde{\gamma}\tilde{\gamma}) &= \frac{\pi s^3}{20\Lambda^8} \approx 61 \left(\frac{s}{\mathrm{Te}V^2}\right)^3 \left(\frac{\mathrm{Te}V}{\Lambda}\right)^8 \ \mathrm{p}b.
\end{aligned} \tag{4}$$

Note that the above given estimates, being obtained from the effective theory, are valid only for energies lower than the cutoff scale $\Lambda$.

As we see, future colliders may have sizeable ability for the mirror matter production. To experimentalists regret, there is no useful signature for such kind of reactions, and a quest for them looks like hunting for the black cat in a dark room. May be more clear signature have reactions accompanied by the initial-state radiation [22]. But we suspect severe background problems here, in particular from the real graviton emission [23]. As for the mirror matter two-photon production, in the equivalent photon approximation [24] we have, for example

$$\sigma(e^+e^- \to e^+e^-\tilde{\gamma}\tilde{\gamma}) = \frac{\alpha^2}{\pi^2}\int\limits_0^1 \frac{dz}{z}\left[f(z)(L-1)^2+\frac{1}{3}\ln^3 z\right]\sigma_{\gamma\gamma\to\tilde{\gamma}\tilde{\gamma}}(zs). \tag{5}$$

Where $L = \ln\frac{s}{m_e^2}$ and

$$f(z) = \left(1+\frac{1}{2}z\right)^2 \ln\frac{1}{z} - \frac{1}{2}(1-z)(3+z).$$

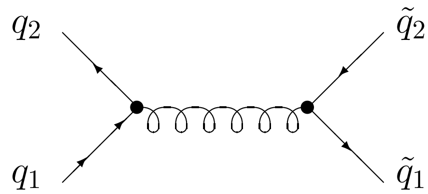
Substituting $\sigma_{\gamma\gamma\to\tilde{\gamma}\tilde{\gamma}}$ from (4) and integrating, we get

$$\sigma(e^+e^- \to e^+e^-\tilde{\gamma}\tilde{\gamma}) = \frac{\alpha^2 s^3}{180\pi\Lambda^8}\left[\frac{121}{400}(L-1)^2-\frac{2}{3}\right]. \tag{6}$$

For $s \approx 1\mathrm{T}eV^2$ this is about $10^4$ times smaller than $\sigma(\gamma\gamma \to \tilde{\gamma}\tilde{\gamma})$ at the same center of mass energy. Besides, considerable background is expected in this channel too. For example, from the real graviton two-photon production [25].

## 3 Quarkonium – mirror quarkonium oscillations

Virtual graviton exchange




leads to the ordinary–mirror matter mixing due to the following low energy effective 4-fermion interaction [21]

$$H = 8\pi C_4 m_q m_{\tilde{q}} \frac{n+1}{n+2} \bar{\psi}\psi\bar{\tilde{\psi}}\tilde{\psi} -$$
$$-\frac{\pi}{2} C_4 \left[ (q_1+q_2)\cdot(\tilde{q}_1+\tilde{q}_2)\bar{\psi}\gamma^\mu\psi\bar{\tilde{\psi}}\gamma_\mu\tilde{\psi} + \bar{\psi}(\hat{\tilde{q}}_1+\hat{\tilde{q}}_2)\psi\bar{\tilde{\psi}}(\hat{q}_1+\hat{q}_2)\tilde{\psi}\right], \quad (7)$$

where $n$ is the number of the large extra dimensions and in numerical estimates we will assume

$$C_4 \sim \frac{1}{\Lambda^4}, \quad \Lambda \sim 1\mathrm{T}eV. \quad (8)$$

As a result of this mixing, heavy C-even quarkonia can oscillate into their mirror counterparts, and hence disappear from our world [26]. The same effect takes place, of course, for the light quarkonia and positronium also, but apparently miniscule magnitudes makes it completely irrelevant in these cases.

Having at hand (7) and using that in the weak binding nonrelativistic limit the state vector of quarkonium can be represented as a superposition of the free quark-antiquark states [27], it is straightforward to calculate quarkonium – mirror quarkonium transition amplitude. For tensor quarkonium (like $\chi_{b2}$) and for its mirror analog we get the following mass matrix

$$\begin{pmatrix} M_\chi & -\epsilon M_\chi \\ -\epsilon M_\chi & M_\chi \end{pmatrix},$$

with

$$\epsilon = \frac{6N_cC_4}{M_\chi}\dot{R}^2(0). \tag{9}$$

Where $M_\chi$ is the quarkonium mass and $\dot{R}(0)$ is the derivative at $r = 0$ of its radial wave function. $N_c = 3$ accounts for quark color.

States with definite $M_\chi(1-\epsilon)$ and $M_\chi(1+\epsilon)$ masses are

$$\chi_+ = \frac{1}{\sqrt{2}}(\chi + \tilde{\chi}), \quad \chi_- = \frac{1}{\sqrt{2}}(\chi - \tilde{\chi}).$$

Therefore, the probability for ordinary quarkonium, with lifetime $\tau_\chi$, to oscillate into the mirror quarkonium and disappear is

$$\mathrm{B}r(\chi \to \tilde{\chi}) = \int\limits_0^\infty e^{-\Gamma_\chi t}\sin^2(\epsilon M_\chi t)\,\frac{dt}{\tau_\chi} = \frac{2(\epsilon M_\chi)^2}{\Gamma_\chi^2 + 4\epsilon^2 M_\chi^2} \approx 2\left(\frac{\epsilon M_\chi}{\Gamma_\chi}\right)^2. \tag{10}$$

Let us estimate this invisible branching ratio for $\chi_{b2}$, for example. The derivative at $r = 0$ of the radial wave function depends on the potential used, but for our purposes the following numbers look realistic [28]

$$\dot{R}(0) \approx 1.4\ GeV^5 \quad \mathrm{a}nd \quad \Gamma_{\chi_{b2}} \approx 200\ keV.$$

Then

$$\frac{\epsilon M_\chi}{\Gamma_\chi} = 6N_C\frac{\dot{R}^2(0)}{\Lambda^4\Gamma_\chi} \approx 1.3\cdot 10^{-7}$$

and

$$Br(\chi_{b2} \to \tilde{\chi}_{b2}) \approx 3\cdot 10^{-14}. \tag{11}$$

The "smoking gun" signal for the mirror world existence would be an observation of $\Upsilon(2S) \to \tilde{\chi}_{b2}\gamma$ decay, which will have very clear signature. The probability for such kind of decay can be estimated to be about $2\cdot 10^{-15}$, from the equation (11) and from the known branching ratio for $\Upsilon(2S) \to \chi_{b2}\gamma$ decay. Unfortunately this seems to be too small to be of practical interest.

## 4 Ordinary luminosity from mirror supernova

As we have seen, mirror matter production in electron–positron collisions can have sizeable magnitude. As a result, some part of a mirror supernova

energy will be released in our world too. Let us estimate this effect, taking into account only $\tilde{e}^+\tilde{e}^- \to e^+e^-$, $\gamma\gamma$ reactions with the total cross section

$$\sigma = \frac{3\pi s^3}{320\Lambda^8}. \tag{12}$$

There are also some other channels for the mirror–ordinary energy transfer (see, for example, analogous considerations for axion emission rates [29], and for graviton emission rates [30]). But our purpose here is just to show that the effect may be significant in principle. So, to estimate the mirror – ordinary energy transfer, we will use the cross section (12).

The ordinary energy emissivity per unit volume per unit time of a mirror supernova core with a temperature $T$ is given by the thermal average over the Fermi-Dirac distribution [29, 30].

$$\dot{q} = \int dn_+\, dn_- \frac{(E_+ + E_-)}{E_+E_-}\{E_+E_-\sqrt{(\vec{v}_+ - \vec{v}_-)^2 + (\vec{v}_+\cdot\vec{v}_-)^2 - v_+^2v_-^2}\}\sigma, \tag{13}$$

where

$$dn_\pm = \frac{2d\vec{q}_\pm}{(2\pi)^3}\left[\exp\left(\frac{E_\pm \mp \mu_e}{T}\right) + 1\right]^{-1}, \tag{14}$$

$\mu_e$ and $-\mu_e$ being the chemical potentials for (mirror) electrons and positrons.

The flux factor $\{E_+E_-\sqrt{(\vec{v}_+ - \vec{v}_-)^2 + (\vec{v}_+\cdot\vec{v}_-)^2 - v_+^2v_-^2}\}$ is separated [31] because it is Lorentz invariant and can be easily calculated in the center of mass frame as being $\frac{1}{2}s$, if the electron mass is neglected. In the supernova frame

$$s = 2E_+E_-(1-\cos\theta_{+-}).$$

Now it is straightforward to perform integrations in (13) and we get

$$\dot{q} = \frac{6T^{13}}{25\pi^3\Lambda^8}[I_5(\nu)I_6(-\nu) + I_5(-\nu)I_6(\nu)], \tag{15}$$

where

$$\nu = \frac{\mu_e}{T} \quad \textit{and} \quad I_n(\nu) = \int\limits_0^\infty dx \frac{x^n}{\exp{(x+\nu)} + 1}.$$

Let us compare (15) to the neutrino emissivity by supernova [32] (only the leading term is shown)

$$\dot{q}_{\nu\bar{\nu}} = \frac{2G_F^2T^9}{9\pi^5}(C_V^2 + C_A^2)[I_3(\nu)I_4(-\nu) + I_3(-\nu)I_4(\nu)], \tag{16}$$

where $C_A = \frac{1}{2}$, $C_V = \frac{1}{2} + 2\sin^2\Theta_W$ and $G_F$ is the Fermi coupling constant. From (15) and (16) we get

$$\frac{\dot{q}}{\dot{q}_{\nu\bar{\nu}}} = \frac{27\pi^2}{25(C_V^2 + C_A^2)} \frac{T^4}{\Lambda^8 G_F^2} \frac{I_5(\nu)I_6(-\nu) + I_5(-\nu)I_6(\nu)}{I_3(\nu)I_4(-\nu) + I_3(-\nu)I_4(\nu)}. \tag{17}$$

For a moderate temperature $T = 30\text{M}eV$, chemical potential $\mu_e \approx 345\text{M}eV$ [30] and $\Lambda \sim 1\text{T}eV$, the last equation gives

$$\frac{\dot{q}}{\dot{q}_{\nu\bar{\nu}}} \approx 1.4 \cdot 10^{-16}. \tag{18}$$

But in the first $\sim 10$ seconds the neutrino luminosity from a supernova is tremendous [33]: $L_{\nu\bar{\nu}} \approx 3 \cdot 10^{45} W$ for each species of neutrino. Therefore a small number (18) translates into the following ordinary luminosity of a mirror supernova $L \approx 4 \cdot 10^{29} W$. This is about $10^3$ times larger than the solar luminosity!

## 5 conclusions

To summarize, if the fundamental scale for quantum gravity is about a TeV and if the Mirror World exists in the same 3-brane where our world resides, we will have new possibilities to probe the Mirror World. Even the near future colliders will have an ability to produce mirror particles. But an experimental signature of such events is unclear. It seems that the Mirror World will not be immediately discovered due to this effect after the large extra dimensions will become an experimental fact (if such an exciting event really happens in future experiments), but the discovery will wait for the detailed theory of quantum gravity and precise experiments.

A clear signal of the Mirror World would be an observation of the $\Upsilon(2S) \to \tilde{\chi}_{b2}\gamma$ decay. But the expected branching ratio $\sim 10^{-15}$ is too small to be observable.

The most drastic impact we have for mirror supernovas. For some 10 seconds they can give a flash in our world brighter than thousand suns! I think it is interesting to look for such events.

Finally, let us note that the effects considered in this paper are caused by the virtual graviton exchange. Therefore they depend only weakly on the number of the large extra dimensions.

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